THE DYNAMICS OF TROPICAL CYCLONES

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LONG-TERM GOALS

The broad objectives of this research effort are to improve our understanding of the dynamics of tropical-cyclone evolution and motion using a combination of analytic techniques, observational case studies and numerical model calculations, and to apply this knowledge to improve numerical forecasting algorithms.

OBJECTIVES

The specific objectives of the current effort are:

1. To continue our study of the dynamical processes in tropical cyclones responsible for sudden track changes;
2. To continue the development of an improved method for introducing synthetic tropical-cyclone-scale vortices into initial analyses of operational forecast models;
3. To review convective parameterization schemes for use in hurricane models;
4. To continue our study of the data requirements for improved hurricane track prediction;
5. To continue our study of the dynamics of binary vortex interaction;
6. To initiate a numerical modelling study of tropical-cyclone - trough interaction
7. To continue our study of the dynamics of the extra-tropical transition of hurricanes;
8. To continue a study of tropical-cyclone intensification using TCM90, European Centre for Medium Range Weather Forecasts (ECMWF) and Australian Bureau of Meteorology Research Centre (BMRC) data sets;
9. To complete a study of the kinematics of vortex asymmetries;
10. To complete our study of the evolution of baroclinic vortices in simplified flow configurations

APPROACH

The approach involves a mix of analytical and numerical model calculations, as well as the analysis of operational and field data. Recent findings from theoretical studies are being applied to the problem of initializing tropical cyclones in numerical forecast models.

WORK COMPLETED

1. Our study of the evolution of baroclinic vortices in simplified flow configurations is nearing completion and we expect to submit at least five papers on this early in 1998. The study

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includes: an investigation of the role of large-scale asymmetries and vertical structure on the motion and evolution of baroclinic vortices in vertical shear; the development of an analytic theory which explains certain characteristics of the motion of baroclinic vortices in vertical shear; a comparison of the prediction of quasi-geostrophic, shallow-water, and primitive-equation models initialized with baroclinic vortices in vertical shear; and a comparison of the evolution of two- and three-dimensional vortices in vertical shear.

2. A study of the dynamics of quasi-stationary spiral bands (Weber, 1997a), polygonal eye walls (Weber, 1997b) and concentric secondary wind maxima (Weber, 1997c) in hurricanes and their impact on vortex motion.
3. The book containing the edited lectures presented at the ONR-co-sponsored NATO Advanced Study Institute on *The physics and parameterization of moist atmospheric convection* held in August 1996 has been completed and is now in print. Progress on a review paper on convective parameterization schemes that have been used in hurricane models has been made.
4. A study of the asymmetric-balance equations and their solution when applied to hurricanes has been completed and a paper on this topic has been accepted for publication (Möller and Jones, 1997)
5. The initialization method for the implementation of synthetic vortices in the BMRC's operational regional model has been improved following model evaluation of specific cases.
6. A new very-high resolution barotropic model has been developed for the investigation of dynamical processes involved in sudden track deflections of tropical cyclones. This was used in the studies in item 2 above.
7. A paper describing a series of observational system simulation experiments investigating the data requirements for reliable analyses of hurricane asymmetries from omega dropwindsonde soundings has been submitted for publication (Smith and Glatz, 1997).
8. An observational case study of the extratropical transition of hurricanes *Felix* and *Iris* in 1995 has been completed and a paper on this topic is in preparation.
9. A study of the evolution of monsoon depressions has been largely completed: two publications are in press (Hell and Smith, 1997, Dengler and Smith, 1997).
10. Interpretations of tropical-cyclone development using various diagnostic quantities such as angular momentum fluxes, potential vorticity fluxes, absolute vorticity fluxes and Eliassen-Palm fluxes have been compared.
11. Seven papers were presented at the AMS Conference on Hurricanes and Tropical Meteorology held in Fort Collins in May 1997 and four at the IAMAS/IAPSO Symposium held in Melbourne in July 1997.
12. Papers from earlier work appeared in 1997 or are in press: these include Dengler and Reeder (1997), Dengler (1997), Smith (1997) and Reeder and Smith (1997).

RESULTS

We have gained a better understanding of the processes which determine the evolution and structural change of hurricane-like vortices in vertical shear. Jones (1995) proposed a mechanism by which hurricane-like vortices are able to resist vertical shear. The development of an analogue model which may be solved analytically and the comparison of two- and three-dimensional vortices have provided evidence in support of this mechanism. We have shown that an initially-symmetric vortex in vertical shear may be strongly distorted, developing asymmetries which affect both its motion and its vertical tilt. An adiabatic vertical circulation and changes in the static stability

develop with implications for the modification of convection in the inner core and thus for tropical cyclone intensity changes. Five publications arising out of this study are in preparation.

Hurricanes *Felix* and *Iris* exhibited rather different behaviour during extratropical transition, especially in regard to the nature of the upper-level trough development. It appears that the location of the tropical cyclone relative to the upper-level trough is important. This implies that a good forecast of extratropical transition requires an adequate representation of the upper-level trough development and an accurate depiction of the tropical cyclone track.

Preliminary results of our study of binary vortices have shown that each vortex recognizes the other primarily as an azimuthal wavenumber-one asymmetry that, in the absence of other processes, would lead to an orbit of the two vortices about each other. An analysis of the asymmetric vorticity structure after removal of the initial symmetric vortices reveals two locally-dominant wave-number one patterns that are responsible for an attraction/repulsion of the two vortices. The origin of these patterns, generated instantaneously by nonlinear advective processes, is the subject of continuing research.

Calculations using the new barotropic model have shown that processes in or near the vortex core are mainly responsible for erratic or looping storm motion as well as for drastic reorganizations of the symmetric storm structure. For example, barotropically-neutral or unstable eigenmodes to a vortex may form into meso-vortices in the core of intense storms producing sudden track changes and major changes of the symmetric storm structure. The existence of concentric secondary eye walls not only leads to a reorganization of the symmetric vortex in question, including changes in intensity, but also to quite large erratic track deflections as a result of barotropic instability. Finally, vortex Rossby waves that occur as a result of the destruction/decay or modification of pre-existing vortex asymmetries may lead to significant track changes.

Theoretical work shows that the pseudo-density-weighted potential vorticity flux, the radial advection of absolute angular momentum, the Eliassen-Palm flux divergence and the absolute vorticity flux are equivalent forcing terms in the equation for the mean tangential component of momentum. This is illustrated by comparisons of the various flux terms for the monsoon depression studied by Hell and Smith (1997). A paper on this work is in preparation.

Our study of the data requirements for determining the azimuthal wavenumber-one flow asymmetry of a hurricane have shown, *inter alia*, that the accuracy of retrieval of this component from omega dropwindsonde soundings depends on the orientation of aircraft flight patterns relative to that of the asymmetry. We have shown also that an increased resolution of data along the flight tracks does not necessarily lead to improved accuracy of retrieval of the asymmetry with the objective analysis method used. This surprising result may be a consequence of the constant influence radius used in the analysis, a factor that is being investigated further.

IMPACT/APPLICATIONS

The improvement of initialization procedures for numerical forecast models is an important application arising from our work. Furthermore, the extratropical transition of tropical cyclones is associated with large forecast errors in medium range weather forecasts. Through our study we aim to highlight the processes which are important for the forecast of extratropical transition.

TRANSITIONS

Our algorithm for inserting asymmetric vortices into forecast models is being used operationally in the BMRC tropical-cyclone analysis scheme and is being tested for possible implementation in the NOAA Hurricane Research Division (HRD)'s VICBAR model.

RELATED PROJECTS

Our work on the structure of tropical cyclones is complementary to that on vortex Rossby waves being carried out by Dr. M. Montgomery's group at the Colorado State University in Fort Collins. Our work on the kinematics of vortex asymmetries and our numerical model study of a monsoon depression has been carried out in collaboration with Dr. D. Keyser's group at the State University of New York at Albany. Both of these groups are sponsored by ONR. Our work on the extra-tropical transition of hurricanes is being carried out in collaboration with Dr. C. Thorncroft, Univ. of Reading and that on initialization schemes with BMRC and HRD.

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